(12)

SCATTERING AND DEPOLARIZATION BY ROUGH SEA
UNIFIED FULL WAVE APPROACH

FINAL REPORT

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PRINCIPAL INVESTIGATOR

NOVEMBER 30, 1990

OFFICE OF NAVAL RESEARCH

CONTRACT/GRANT NUMBER

N00014-87-K-0177

PERIOD COVERED
BY REPORT

1 MAY 1987-1 OCTOBER 1990

UNIVERSITY OF NEBRASKA-LINCOLN

SECURITY CLASSIFICATION OF THIS PAGE

A

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) #7	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION University of Nebraska-Lincoln Electrical Engineering Dept.	6b. OFFICE SYMBOL (If applicable)
6c. ADDRESS (City, State, and ZIP Code) WSEC 209N University of Nebraska-Lincoln, NE 68588-0511	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research
	7b. ADDRESS (City, State, and ZIP Code) Code 121 ONR 800 North Quincy Street Arlington, VA 22217-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Office of Naval Research	8b. OFFICE SYMBOL (If applicable)
	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-87-K-0177
8c. ADDRESS (City, State, and ZIP Code) Code 121, ONR 800 North Quincy Street Arlington, VA 22217-5000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
"SCATTERING AND DEPOLARIZATION BY ROUGH SEA--UNIFIED FULL WAVE APPROACH"

12. PERSONAL AUTHOR(S) EZEKIEL BAHAR

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM 5-1-87 TO 10-1-90	November 30, 1990	83

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Navy position, policy, or decision unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
ELECTROMAGNETIC SCATTERING, DEPOLARIZATION, FULL WAVE, GEOMETRIC/PHYSICAL OPTICS, SMALL PERTURBATION, TWO SCALE MODEL, SPECULAR POINTS, SCATTERING CROSS SECTIONS, SYNTHETIC APERTURE RADAR, REMOTE SENSING

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

During the period of this contract (May 1, 1987-October 1, 1990) the principal investigator presented twenty-two (22) papers at scientific/technical meetings (see Item 7.1a) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item 7.1b). Twenty-four (24) papers were submitted to Journal Editors for review (see Item (7.2)) and sixteen (16) were accepted for publication (see Item (7.3)). Ninteen (19) papers were published in journals and conference proceedings (see Item (7.4) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. Three (3) M.S. Theses have been completed during this reporting period (see Item (7.5)), copies were submitted with the Progress Reports) Two (2) Ph.D. Dissertations based on the research conducted under this contract will be completed by the end of next year (see Section 4). Details of the research results are provided in the reprints submitted with the Semiannual Progress Reports and the preprints of manuscripts sent directly to the Project Monitor.

(continued on next page)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

(B)

Name of the → researcher

The principal results are summarized here.

1. Computer simulation of Synthetic Aperture Radar (SAR) polarimetric images of rough sea with swell were obtained from the computed Mueller matrix elements for an individual resolution cell. The modulation of the like and cross polarized scattering cross sections of a SAR resolution cell due to tilts of the mean surface in and perpendicular to the reference (fixed) plane of incidence were computed using the unified full wave approach.
2. Two separate approaches have been developed to account for multiple scatter from rough surfaces. This first approach involves a second order iterative solution. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes.
3. In the high frequency limit shadowing is accounted for by limiting the angles of incidence and scatter to less than 90^0. This is referred to as self-shadow. In addition shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self-shadow.
4. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work a broad family of non Gaussian probability density functions are considered. These are based on the gamma functions of order K. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate statistical characterization of the surface under observation.
5. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions. Both Gaussian and non Gaussian spectral density functions have been considered in this work.
6. The medium below the rough interface is characterized by its complex permittivity and permeability so that conduction currents and displacement currents are accounted for in the analysis.
7. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface heights and slopes are statistically uncorrelated. In an attempt to examine the validity of the assumption random rough surfaces are characterized by four dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points.
8. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) has been examined in some detail. It is shown that at oblique angles ($\theta_0 > 20^0$) single scatter is the principal contributor to the observed enhanced backscatter while for near normal incidence the singly scattered and multiple scattered contributions to the field add constructively or destructively about the backscatter direction.
9. Investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks, ship wakes, swells and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.
0. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves. The results can be applied directly to polarimetric remote sensing.
1. As in the past several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach. To this end the full wave unified and two scale solutions have been used to interpret the Apollo lunar data.
2. The single scatter programs have been transferred to the College of Engineering VAX. The programs are in Fortran IV. A concerted effort has also been made to enhance our ability to graphically represent our data. At present the computations of the multiply scattered field are executed on the Supercomputer facility at Cornell University. This computational work is supported through an NSF supercomputer grant.

→ Keywords: Backscattering/spectral; Backscattering;
Electromagnetic wave propagation;
Spectral energy distribution;
Radar imaging;
Optical cross section;
Ocean surface/roughness; Perturbation theory;
Computerized simulation.

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1. INTRODUCTION

STATEMENT OF THE PROBLEM

I. INTRODUCTION -- STATEMENT OF THE PROBLEM

Numerous scattering theories have been developed to determine the scattering and depolarization of electromagnetic waves from deterministic and randomly rough surfaces. However, the most commonly used theories, based on the physical optics and the small perturbation approaches, cannot be applied to composite surfaces, characterized by a broad range of roughness scales. In addition, several computer programs have been developed to numerically solve the integral equations for the scattered fields. These numerical solutions have limited use since they are restricted to one dimensionally rough surfaces even when supercomputers are used. Several hybrid solutions based on two scale models of the rough surfaces have also been introduced to overcome these difficulties. They are based on a combination of the physical optics (Beckmann and Spizzichino 1963), and the small perturbation (Rice 1951) approaches. Thus, a surface with small scale roughness is assumed to ride on the large scale (filtered) surface and the solution is expressed as a sum of two cross sections, one associated with the large scale surface and the other associated with the small scale surface (Valenzuela 1968, Wright 1968). The difficulties with the hybrid approach based on the two scale model, lies in the determination of the spatial wavenumber that separates the large scale surface from the small scale surface and in the underlying assumption that these two rough surfaces can be regarded as statistically independent. The large scale (filtered) surface is assumed to be sufficiently smooth such that it satisfies the large radii of curvature restriction imposed when the physical optics approach is used. The small scale surface is assumed to have a sufficiently small mean square height and slope in order to satisfy the small perturbation assumptions.

These restrictions cannot in general be satisfied simultaneously and the physical optics approach does not account for the backscattered cross polarized fields. Therefore, these two scale solutions critically depend on the choice of the spatial wavenumber where spectral splitting between the large and small scale surfaces is assumed to occur (Brown 1978). Furthermore, even for surfaces that simultaneously satisfy the large radii of curvature restriction (inherent in the physical optics approach) and the small height and small slope limitation (assumed when the perturbation approach is used), the two commonly used physical optics and small perturbation solutions are not in agreement.

Since the sea surface consists of a broad range of roughness scales, it is important to employ a rough surface theory that is not encumbered by the limitations of the physical optics, perturbation or the hybrid solutions based on two scale models. In order to utilize or reduce the effects of sea clutter in radar systems, the rough surface theory must also be applicable to real and/or Synthetic Aperture Polarimetric Radars. Thus, in general, it is necessary to completely characterize the radar returns from the rough sea by the sixteen elements of the Mueller matrix that relate the incident Stokes vector to the scattered Stokes vector (Bahar and Fitzwater 1989).

The full wave approach that is based on the complete expansion of the electromagnetic fields and on the imposition of exact boundary conditions (Bahar 1973a,b; 1974) is used to determine the singly and multiply scattered fields from surfaces that are either characterized deterministically or statistically. These full wave solutions are invariant to coordinate transformations and they satisfy the reciprocity, realizability and duality relationships in electromagnetic theory. Both the small perturbation solutions as well as the physical optics solution can be obtained directly from the full wave solutions. Furthermore, using

hindsight it is possible to derive the full wave single scatter, far field solution directly from the perturbation solution by subjecting the perturbation solution to a set of coordinate transformations as well as a phase modification which correctly accounts for the surface height fluctuations. Thus, using the full wave approach, it is possible to determine the direct relationship between the small perturbation solution and the physical optics solution.

It is shown that if in the integrand of the expressions for the scattered fields, the unit vector $\bar{n}$ normal to the rough surface is replaced by its value $\bar{n}_s$ at the stationary phase points (before integration) the full wave solutions reduce to the physical optics solutions (Beckmann and Spizzichino 1963). Therefore, for the physical optics approach to be valid in the high frequency limit, it is not only necessary for the radii of curvature to be large compared to wavelength, but the major contributions to the scattered fields must come from the vicinity of the stationary phase (specular) points of the rough surface. This is a principal reason why the physical optics approach cannot be used to correctly predict the enhanced backscattered fields even at optical frequencies (Bahar and Fitzwater 1989). If the integral for the scattered fields is evaluated analytically using the stationary phase approximation the full wave solution reduces to the Geometric Optics solution.

The direct link between the full wave soluiton and the low frequency small perturbation solutfon is obtained when in the integral expression for the scattered fields, the unit vector $\bar{n}$ normal to the rough surface is replaced by the unit vector $\bar{a}_y$ normal to the reference (mean) plane y=o, (negligible slopes) and in addition,

if the exponential function $\exp(ik_o(\bar{n}^f-\bar{n}^i)\cdot h(x,z)\bar{a}_y)$ is replaced by the first two terms of its Taylor series expansion $1 + iv_y h = 1 + ik_o h(\bar{n}^f - \bar{n}^i)\cdot\bar{a}_y$, the full wave solution reduces to the sum of the reflected field from the flat (unperturbed) surface and the diffuse scattered field derived by Rice, based on the small perturbation approach. On hindsight it is therefore possible to trace the rather elusive relationship between the small perturbation (low frequency) solution and the high frequency physical optics solution even though the two solutions are not in agreement for surfaces that simultaneously satisfy the small perturbation restrictions and the large radii of curvature criteria. To this end, one can start with Rice's polarization dependent small perturbation solution for the fields scattered by a surface element dA in the neighborhood of the point $\bar{r}$ on the rough surface. At the point $\bar{r}$, the normal to the surface element at height y=h(x,z) is given by the unit vector $\bar{n} = \nabla f/|\nabla f|$, where f = y-h. Thus, on subjecting Rice's solution to the principle of invariance under coordinate transformations and replacing the factor appearing in his solution $ik_o h(\bar{n}^f-\bar{n}^i)\cdot\bar{a}_y$ (associated with the surface height fluctuations) by the exponential function $\exp(ik_o(\bar{n}^f-\bar{n}^i)\cdot h(x,z)\bar{a}_y)$ (associated with the corresponding phase fluctuation), Rice's solution is transformed into the full wave solutions for the singly scattered radiation (far) fields. If, at this point the value for the unit vector $\bar{n}$ normal to the rough surface is replaced by its value $\bar{n}_s$ at the stationary phase (specular) points, the low frequency small perturbation solution transforms directly into the high frequency physical optics solution.

The inter-relationships between the small perturbation, the full wave, the physical/geometric optics and the hybrid solutions (based on two scale models of the rough surface) are shown schematically in Fig. 1. Thus, when one applies the full wave approach to evaluate the fields scattered by composite surfaces consisting of a very broad range of roughness scales, it is not necessary to adopt the two scale model of the rough surface.

Since the distinction between different roughness scales is made relative to the electromagnetic wavelength, the full wave approach is also applicable to scattering problems with transient or broad spectral excitations for both real and synthetic aperture radars.

For radar remote sensing application, the random rough surfaces are usually characterized by their normalized like and cross polarized diffuse scattering cross sections $\langle\sigma^{PQ}\rangle(P,Q=V,H)$. The normalized scattering cross sections therefore relate the diffuse (total minus the coherent) scattered intensity (with polarization P=V,H) to the incident intensity (with polarization Q=V,H). Similar expressions for the scattering cross sections can be written in general for elliptical incident and scatter polarization. However, for the purposes of enhancing or suppressing special features of the radar returns, the optimal polarizations of the transmitter and receiver are not known a priori. In these cases, it is necessary to characterize the scattered fields by the 4x4 Stokes matrix elements which contain both magnitude and relative phase data. The Stokes matrix relates the scattered Stokes vector elements to the incident Stokes vector elements.

Explicit full wave expressions for all sixteen elements of the Stokes matrix need to be evaluated in order to obtain a complete

polarimetric description of the rough surface scattered field. Extensive work has been carried out to determine the optimum polarization of the transmitter/receiver to enhance special features of the radar signals. Multifrequency polarimetric radar systems provide improved capabilities to enhance or suppress these features (Zebkar et al. 1990). The Stokes matrix is also useful for Synthetic Aperture Radar (SAR) applications.

2. SUMMARY OF RESULTS

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During the period of this contract, May 1, 1989 - October 1, 1990, the principal investigator presented twenty-two (22) papers at scientific technical meetings (see item (7.1a)) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item 7.1b)). Twenty-four (24) papers were submitted to journal editors for review (see Item (7.2)) and sixteen (16) were accepted for publication (see Item (7.d)). Nineteen (19) papers were published in journals and conference proceedings (see Item (7.4)) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. Three (3) M.S. Theses have been completed during this reporting period (see Item (7.5)), copies were submitted with the semiannual Progress Reports. Two (2) Ph.D. Dissertations based on the research conducted under this contract will be completed by the end of next year (see Section 4).

Details of the research results are provided in the reprints submitted with the Semi Annual Progress Reports and the preprints of manuscripts sent directly to the project monitor.

The principal results are summarized here.

1. The like and cross polarized scattering cross sections of a Synthetic Aperture Radar (SAR) resolution cell is subject to modulation when the mean plane of the resolution cell is tilted in or perpendicular to a fixed reference plane of incidence. The unified full wave solutions have been used to derive the tilt

modulation of the scattering cross section for the SAR resolution cell. All the scales of roughness of the resolution cell were accounted for in a unified self-consistent manner for all angles of incidence.

Computer simulations of Synthetic Aperture Radar polarimetric images of rough sea with swell were also obtained from the computed Mueller matrix elements for an individual resolution cell. This work is reported in detail in the M.S. Thesis of R. D. Kubik (see Item (7.5)). Samples of three computer simulations of SAR polarimetric images are shown in Figures 2, 3 and 4.

2. Two separate approaches have been developed to account for multiple scatter from rough surfaces. The first approach involves a second order iterative solution. In the high frequency limit it is shown that these results correspond to one bounce (single scatter) and two bounces (multiple scatter) of the incident wave from the surface. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes. To this end the radiation wave spectrum is discretized and the resulting set of first order coupled differential equations are solved numerically. This work is currently in progress and only preliminary results have been obtained. This numerical solution contains the total field (the single and the multiple bounce contributions). Only one dimensionally rough surfaces are considered when this numerical approach is used.

3. In the high frequency limit shadowing is accounted for by limiting the local angles of incidence and scatter to less than 90^{o}. Thus, if $\bar{n}$ and $\bar{n}^{i}$ are unit vectors normal to the surface and in the direction of propagation respectively, then this condition is satisfied if $-\bar{n}^{i} \cdot \bar{n} > 0$. This is referred to as self-shadow. In addition, it is assumed in the high frequency limit, that the fields vanish below the local tangent planes at the points where $\bar{n}^{i} \cdot \bar{n} = 0$. This shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self-shadow since the fields below this local tangent plane cannot be ignored.

4. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work, a broad family of non Gaussian probability density functions are considered. These are based on the Gamma functions of order K. For K = 1, the marginals of the joint probability density function of the surface height is exponential while for $K \to \infty$ (for all practical purposes $K \geq 25$) the marginals reduce to the Gaussian probability density function. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate probability density function (order K) that most closely represents the statistical characterization of the surface under observation.

5. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions for the surface heights at two separate points. To this end it is also necessary to know the surface height spectral density function. Both Gaussian and non Gaussian spectral density functions have been considered in this work.

6. The medium below the rough interface is characterized by its complex permittivity and permeability. Thus conduction currents and displacement currents are accounted for in the analysis. In limiting cases, both perfect conductors and perfect dielectrics can be considered for the reflection as well as the transmission scattering problems.

7. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface height and slopes are statistically uncorrelated. In an attempt to examine the validity of this assumption random rough surfaces that vary in height, only in one dimension, are examined in detail. In order to simplify the analytical expressions for the scattered fields, the surface is also assumed to be perfectly conducting. Thus, these random rough surfaces are characterized by four dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points. The surfaces are also assumed to be slightly rough in order to determine the conditions for the

coalescence of the full wave solutions with the small perturbation and specular point solutions. A preprint of this paper has been sent to the Project Monitor.

8. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) have been examined in some detail. The effects of varying the angles of incidence, the material below the interface, the surface mean square slope and height and the rough surface correlation lengths are considered. It is shown that at oblique angles ($\theta_0 > 20^0$) single scatter is the principal contributor to the observed enhanced backscatter, while for near normal incidence the single scattered and multiply scattered contributions to the field add constructively or destructively about the backscatter direction.

9. During this reporting period several investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks naturally occurring or due to (deliberate or accidental oil spills) ship wakes, swells and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.

10. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves, including the special cases; vertically, horizontally, right and left circular polarized waves. In addition, all sixteen elements of the

Mueller matrix can be computed using the full wave approach. Thus, these results can be applied directly to polarimetric remote sensing.

11. As in the past, several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach.

12. The University of Nebraska is currently in the process of setting up an optical scatterometer and Scanning Tunnelling Microscope facility (with a 75 micrometer dual scan for the STM and the Atmoic Force Microscope for conducting and non conducting surfaces). Therefore, current attempts at experimental validation are restricted to comparison with data obtained from external sources. To this end, the full wave unified and two scale solutions have been used to interpret the Apollo lunar data. This data represents quasi-specular reflection (from Apollo 14 through 16) off the moon surface to the earth at angles of incidence from about 10^{o} to 85^{o}. The full wave solution properly accounts for the significant rise in the normalized scattering cross section at around 80^{o} just before rough surface shadowing needs to be accounted for in the analysis.

The full wave solutions, with the single and multiply (two bounce) contributions accounted for in the analysis of scattering from very rough surfaces, provide an analytical/physical interpretation of the observed enhanced backscatter at both normal and oblique incidence.

The single scatter programs that were executed previously on the CDC computers at the University have been transferred to the College of Engineering VAX. The programs are in Fortran IV and batch jobs are usually executed within 24 hours. Smaller jobs can be executed practically in real time. A concerted effort has also been made to enhance our ability to graphically represent our data.

At present the computations of the multiply (two bounce) scattered field are executed on the Supercomputer Facility at Cornell University. This computational work is supported through an NSF Supercomputer Grant. Magda El-Shenawee (Ph.D. student) has taken two short courses at Cornell University on the efficient use of Supercomputers.

3. DESCRIPTION OF RESEARCH

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Detailed description of the analytical and numerical techniques used in these investigations and their applications to engineering and technology are given in the reprints and preprints of the scientific manuscripts submitted with the six (6) Semi Annual Progress Reports (see List of Publications, Section 7).

4. PERSONNEL SUPPORTED BY THIS PROJECT

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In addition to the principal investigator, Ezekiel Bahar, the main contributors to this research project are Mary Ann Fitzwater (Research Associate through 1988), and five (5) Graduate Research Assistants).

During this reporting period the following students received their M.S. degrees in Electrical Engineering. Copies of their theses were submitted with the Semi Annual Progress Reports (see Item (7.5)).

(i) Robert D. Kubik

(ii) Yan-Feng Li

(iii) Guorong Huang

The Ph.D. dissertation of Magda El-Shenawee and Xiaochuan Shi should be completed by the end of next year.

5. ACKNOWLEDGMENTS

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The author wishes to thank Dr. David Johnson (ONR, Washington, D.C.), for his encouragement and continued interest in these investigations.

The author also wishes to acknowledge the support he received from the University of Nebraska-Lincoln for use of its computing facilities. He is especially indebted to the National Science Foundation for the Engineering Supercomputer Grants he was awareded in order to use the University of Cornell's Supercomputer facility.

This manuscript was prepared by Eunice Everett.

6. CONCLUDING REMARKS

6. CONCLUDING REMARKS

The research group at the University of Nebraska-Lincoln has over the three year duration of the ONR contract, satisfied all the research objectives in the original proposal. Several new objectives need to be considered for future work in this field. To exploit recent advances in polarimetric radar techniques, it is necessary to evaluate all the sixteen (16) Mueller matrix elements (not only the scattering cross sections). For slightly rough surfaces it is necessary to evaluate both the coherent and incoherent scattering cross sections. This would significantly contribute to resolving some of the questions raised recently on the validity of the small perturbation and Kirchhoff approaches to rough surface scattering. In addition, excitation by real sources rather than uniform plane wave, should be considered.

Suggested topics for future consideration by the researchers at the University of Nebraska, are listed below.

1. Use rigorous mathematical/physical models of pertinent engineering/scientific problems and employ a judicious combination of theoretical, applied and computational mathematics to solve them. These solutions should be applicable to a very broad class of rough surfaces and to ultra wideband radars. No artifical scaling parameters or "effective" median parameters should be used in this work.

2. Develop techniques to discriminate between clutter and radar signatures from specific targets. This work will facilitate the utilization or reduction of the effects of sea clutter for real and synthetic aperture radars. Special consideration should also be given to the existence of transmission windows in either the frequency domain or the spatial (angular) domain.
3. Full wave solutions for the (4 x 4) Mueller matrix elements should be used to evaluate polarimetric radar techniques for target/clutter discrimination.
4. Analytical and numerical determination of the like and cross polarized multiple scatter contributions to the total scattered field from one and two dimensionally rough surfaces.
5. Consider the effects of rough surface height and slope correlations on the evaluation of the like and cross polarized scattering cross sections of one and two dimensionally rough surfaces. Thus, the random rough surface is characterized in general by a six (6) dimensional joint probability density function for heights and slopes at two points.
6. Consider the impact of self-shadow (due to restrictions on local angles of incidence and scatter) and the impact of shadowing due to neighboring surface obtrusions, on the scattered field.
7. For slightly rough surfaces, both the coherent and incoherent scattering cross sections should be evaluated.

8. Excitation by real sources rather than uniform plane waves should be considered.
9. Remote sensing techniques to detect ship wakes and oil slicks should be explored further using both real and synthetic aperture radars.
10. A major effort can now be made to compare the analytical/numerical results with both in situ measurements (over the earth's surface) as well as controlled laboratory experiments. To this end, the Electrical Engineering Department is setting up an optical scatterometer, microwave anechoic chamber and tunnelling microscope facility in conjunction with the Center for Electro-Optics in the College of Engineering and Technology.

The Principal Investigator has had wide experience in constructing laboratory models (earth-ionosphere waveguide) to experimentally examine the validity of analytical/numerical solutions. He has compared the predictions based on the full wave analysis with in situ experimental data over the earth's surface as well as with controlled laboratory experiments. He has interest and experience to conduct research in analytical, numerical and experimental areas listed above.

7. LIST OF PUBLICATIONS BY THE PRINCIPAL INVESTIGATOR DURING PERIOD OF NAVY CONTRACT

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

(i) XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24-September 2, 1987. Paper Presented "Radar Cross Sections of Rough Terrain and Vegetation Covered Terrain," Member of U.S. National Research Council Delegation.

(ii) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988, "Scattering and Depolarization by Two-Dimensional Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

(iii) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, New York, June 6-11, 1988. "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."

(iv) 1988 International Geoscience and Remote Sensing Symposium, Edinburgh University, Edinburgh, United Kingdom, September 13-16, 1988. "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," (FRA-221).

(v) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Scattering Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(vi) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989, "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. Fitzwater.

(vii) IEEE AP-S International Symposium and URSI Radio Science Meeting, June 26-30, 1989, San Jose, California, "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."

(viii) 1989 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 26-30, 1989, "Transmission Scattering and Depolarization Across Rough Surfaces-Full Wave Solutions," with Guorong Haung.

(ix) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(x) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and Two Scale Full Wave Approach," with M. Haugland.

(xi) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."

(xii) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."

(xiii) National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel Member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, Massachusetts. Invited Paper on "Electromagnetic Scattering by Randomly Rough Boundaries."

(xiv) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989, "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(xv) International Union of Radio Science Commission F Symposium on Radio and Nonionized Media at La Londe-les-Maures, France, September 11-15, 1989, "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik.

(xvi) Scientific Conference on Chemical Defense Research, U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, Maryland, November 14-17, 1989, "Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach," with S. M. Haugland and A. H. Carrieri.

(xvii) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 3-5, 1990, "Electromagnetic Scattering and Depolarization Across Rough Surfaces--Full Wave Solution," with G. Huang.

(xviii) First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos National Laboratory, March 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(xix) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee.

(xx) International Union of Radio Science (URSI), Commission F, Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, Hyannis, MA, May 16-18, 1990, "Remote Sensing of the Sea Surface Contaminated by Monomolecular Oil Slick: Full Wave Approach," with R. Kubik.

(xxi) 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties, University of Maryland, College Park, MD, May 20-24, 1990, "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections: Full Wave Approach," with Y. F. Li.

(xxii) 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 25-28, 1990, "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with Mark Haugland.

(7.1b) Papers Accepted for Presentation at Technical Meetings, After June 30, 1990.

(i) XXIIrd General Assembly of the International Union of Radio Science, Prague, Czechoslovakia, August 28-September 5, 1990, "Radiowave Propagation Over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters," Invited Paper.

(ii) International Union of Radio Science Symposium on Scattering from Random Media (Joint Session B/F), Prague, Czechoslovakia, August 28-September 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces."

(iii) Advisory Group for Aerospace Research and Development Fall 1990, Electromagnetic Wave Propagation Panel Symposium on Use or Reduction of Propagation and Noise Effects in Distributed Military Systems, Rethymo, Crete, Greece, October 15-19, 1990, "Utilization or Reduction of the Effects of Sea Clutter for Real and Synthetic Aperture Polarimetric Radars."

(iv) The Fourth Biennial IEEE Conference on Electromagnetic Field Computation, Toronto, Canada, October 22-24, 1990, "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee.

(v) 1990 U.S. Army Chemical Research Development and Engineering Center Scientific Conference on Chemical Defense Research, Aberdeen, MD, November 13-16, 1990, "Computation of Mueller Matrix Elements for Irregular Stratified Media--Full Wave Approach," with Mark Haugland.

(7.2) Papers Submitted to Journal Editors for Review

(i) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater.

(ii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

(iii) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater.

(iv) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater.

(v) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater.

(vi) "Synthetic Aperture Radar Images for Swell Using the Unified Full Wave Method," with R. D. Kubik.

(vii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik.

(viii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland.

(ix) "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(x) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Appraoch," with R. Kubik.

(xi) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper on Review of Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel.

(xii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."

(xiii) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions."

(xiv) "Unified and Two Scale Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland.

(xv) "Tilt Modulation of Synthetic Aperture Radar Backscatter Cross Sections: Unified Full Wave Approach," with R. Kubik.

(xvi) "Computer Simulation of Synthetic Aperture Polarimetric Images - Unified Full Wave Approach," with R. Kubik.

(xvii) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with G. Huang.

(xviii) "Scattering Cross Sections for Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach," with Y. F. Li.

(xix) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach," with Y. F. Li.

(xx) "Statistics for Identifying Contaminated Rough Surfaces by Polarized IR Scattering: Full Wave Approach," with S. M. Haugland and A. H. Carrieri.

(xxi) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee.

(xxii) "Acoustic Scattering by Two-Dimensionally Rough Interfaces Between Dissipative Acoustic Media - Full Wave, Physical Acoustics and Perturbation Solutions."

(xxiii) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions." Revised.

(xxiv) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li.

(7.3) Papers Accepted for Publication

(i) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, Optics Communications, Vol. 63, No. 6, pp. 355-360, September 1987.

(ii) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A, in press.

(iii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, in press.

(iv) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction, in press.

(v) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187, April, 1988.

(vi) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Ocean, in press.

(vii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 6 33-43, January, 1989.

(viii) "Non Specular Scattering by Irregular Layered Media," Proceedings of the 1988 Scientific Conference on Obscuration and Aerosol Research, in press.

(ix) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, July 10-14, 1989, Vancouver, Canada, in press.

(x) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, July 4-10, 1989, Vancouver, Canada, in press.

(xi) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 146-147, July 1989.

(xii) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, Stockholm, Sweden, August 14-17, 1989, in press.

(xiii) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France, September 11-15, 1989, in press.

(xiv) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research, Boston, Massachusetts, July 29, 1989, in press.

(xv) "Full Wave Solutions for the Scattering of Acoustic Waves Excited by Arbitrary Source Distributions in Irregular Layered Media," Wave Motion, in press.

(xvi) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

(7.4) Papers Published in the Technical Literature and Submitted with the Six Semi-Annual Reports

(i) "Comparison of Unified Full-Wave Solutions for Normal-Incidence Microwave Backscatter from Sea with Physical Optics and Hybrid Solutions," with D. E. Barrick and M. A. Fitzwater, International Journal of Remote Sensing, Vol. 9, No. 3, pp. 365-377, 1988.

(ii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 3, 199-218, July, 1988.

(iii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Wave Propagation and Scattering in Varied Media, Vol. 927, 78-87, April 6-8, 1988.

(iv) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 5, 1873-1883, November, 1988.

(v) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187,

(vi) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 6, pp. 33-43, January, 1989.

(vii) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Oceans, Vol. 94, No. C2, pp. 2159-2169, February, 1989.

(viii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, IEEE Transactions on Antennas and Propagation, Vol. AP-S 37, No. 12, pp. 1609-1616, December, 1989.

(ix) "Non Specular Scattering by Irregular Layered Media," Proceedings 1988 Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, CRDEC-SP pp. 1-8, 1989.

(x) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, July 10-14, 1989.

(xi) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada,

(xii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 146-147, July, 1989.

(xiii) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 398-399, July, 1989.

(xiv) "Scattering of Acoustic Waves in Irregular Layered Media - Full Wave Solutions, Wave Motion, Vol. 12, pp. 53-65, January, 1990.

(xv) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, Stockholm, Sweden, pp. 503-505, August 14-17, 1989.

(xvi) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France, pp. 7.1.1 - 7.1.4 September 11-15, 1989.

(xvii) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Directions in Electromagnetic Research, Boston, MA, pp. 311-314, July 29, 1989.

(xviii) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

(xix) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li, Proceedings of the International Geoscience and Remote Sensing Symposium, Vol. II, 1401-1403, May, 1990.

(7.5) M.S. Theses Completed During This Reporting Period

(i) "Scattering Cross Section Modulation of a Synthetic Aperture Radar Resolution Cell with Application to SAR Imaging Unified Full Wave Approach," by Robert D. Kubik.

(ii) "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution," by Yan-Feng Li.

(iii) "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces - Full Wave Approach," by Guorong Huang.

8. APPENDIX

SEMI-ANNUAL PROGRESS REPORTS NOS. 1-6

PROGRESS REPORT # 1

1. SFRC Number: N00014-87-K-0177

2. PERIOD COVERED: May 1, 1987 - February 15, 1988

3. TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

4. SPONSOR: Office of Naval Research

5. SCIENTIFIC PROGRAM OFFICER: Dr. R. J. Hansen

6. PRINCIPAL INVESTIGATOR: Ezekiel Bahar

7. NAME OF INSTITUTION: University of Nebraska-Lincoln

8. AUTHOR OF REPORT: Ezekiel Bahar

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD

See Attached List

10. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator

Research Associate Dr. M. A. Fitzwater

DATE SUBMITTED: February 23, 1988

Ezekiel Bahar
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9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD.

(9.1) Papers Presented at Technical Meetings

(i) XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24-September 2, 1987. Paper Presented "Radar Cross Sections of Rough Terrain and Vegetation Covered Terrain," Member of U.S. National Research Council Delegation.

(9.2) Papers Submitted to Journal Editors for Review

(i) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M.A. Fitzwater, submitted for review.

(9.3) Papers Published in the Technical Literature and Submitted with this Report

(i) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M.A. Fitzwater, Optics Communications, Vol. 63, No. 6, pp. 355-360, September 1987.

(9.4) Preprints of Manuscripts (work in Progress) to be Submitted for Journal Review

(i) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell."

OUTLINE OF RESEARCH FINDINGS

During this reporting period (May 1, 1987 - Feb. 15, 1988), the Principal Investigator presented an invited paper at the XXIInd General Assembly of the International Union of Radio Science (see Item (9.1))i). He also attended the URSI General Assembly as an official U.S. Delegate appointed by the U.S. National Research Council. One technical/scientific manuscript was submitted for publication (see Item (9.2)(i)), preprint submitted to scientific program officer). One paper was published in Optics Communications (see Item (9.3)(i)) and a manuscript on the backscatter cross sections of an anisotropic rough sea surface with swell has been prepared (see Item (9.4)(i)) and submitted to the scientific program officer with this progress report. It will also be submitted for review.

Rob Kubik (M.S. Graduate Student) represented the University of Nebraska-Lincoln research program at the ONR Ship Wake Program Review held at Dynamics Technology, Inc., California on December 10-11, 1987.

The full wave solutions for the bistatic like and cross polarized scattering cross sections of rough surfaces were compared with a series of measurements taken in a controlled laboratory environment by Mendez and O'Donnell at Imperial College, London, England (see enclosure from R&D Roundup - Microwaves RF, August 1987). The observed like and cross polarized backscatter enhancement was predicted as a first order effect on the basis of an iterative-closed form solution to the full wave-telegraphists' equations. This approximation of the full wave solution therefore does not account for multiple scattering by the rough surface. At present the principal investigator has also derived analytical expressions for the second order-multiply scattered field and this work, in its two dimensional version (one dimensional rough surface) has

been given to a graduate student for the purpose of preparing a computer code to calculate the second order multiply scattered fields. The information derived from this phase of the research project is to be used to generate criteria regarding the cases for which multiple scatter significantly modifies the first order results and to determine the major impact of multiple scatter on the total scattered field--whether it is a very diffuse contribution or whether (as some conjecture), it contributes to the observed enhanced backscatter.

The full wave solutions for the horizontally polarized bistatic scattering cross sections of one dimensional perfectly conducting surfaces were also compared with the computer data obtained with a Monte Carlo technique. At present the full wave computer code is being modified to account for all the correlations between the slopes and heights at two points on the rough surface. This phase of the research project may have to be executed on a supercomputer.

Using the full wave approach, it is shown that the like polarized backscatter cross sections for anisotropic rough seas depend on the direction of the normally incident electric field with respect to the orientation of the remotely generated swell. Furthermore, for normal incidence the full wave cross polarized backscatter cross sections which are also dependent on the surface height parameters of the swell are significantly larger than the computed cross sections based on the two-scale model of the rough sea. These results suggest a method for the remote sensing of the surface height parameters of the swell and its orientation as well as the velocity of the local wind at the sea surface.

WAVE PROPAGATION

Although electromagnetics is a mature science, new problems are challenging the theoreticians.

WALTER A. FLOOD,

Director, US Army Research Office, Geosciences Div., P.O. Box 12211, Research Triangle Park, NC 27709-2211; (919) 549-0641

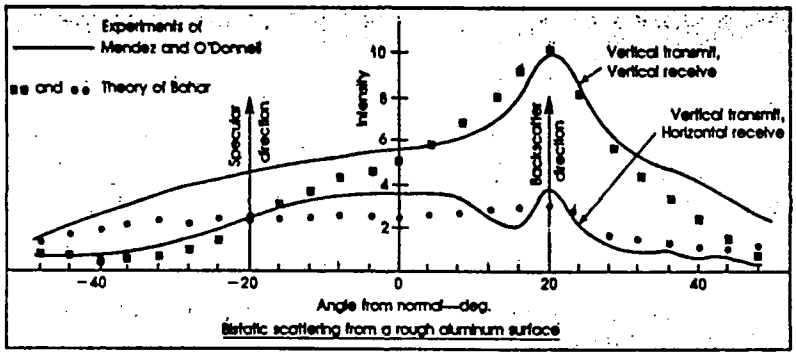
Results of some innovative experiments in the scattering of electromagnetic waves by particles and rough surfaces are not predicted by existing mathematical theory. Discussion of a few of these innovative experiments will indicate the lack of physical theories to explain them. Because of the significance of the experiments, the literature in which they appear is listed here.

The first two experiments[1,2] involve multiple scattering by particles and the need to account for correlation between pairs of particles. These experiments were performed at optical wavelengths and reported in optical journals. Although they are relevant to radar clutter and remote-sensing problems, they may have been missed by the high-frequency community.

The third set of experiments[3] is relatively new. The data were first published in January 1987, again in an optical journal. These results formed the basis of a special session of the January 1987 Radio Science Symposium (Boulder, CO). The data show that when a sufficiently rough surface (i.e., large RMS slopes and large height fluctuations measured in wavelengths) is illuminated by a coherent field, the major electromagnetic field return is in the antispecular or backscattering direction. This result appears to be true for all angles of incidence of the EM wave.

These experimental results have truly challenged theoreticians. In addition, the experiments provide a set of well-characterized surfaces against which to exercise theories and models currently used in remote-sensing, propagation and clutter research. Although there is no surface-scattering theory available that can explain these data, one theory—the full-wave theory proposed by Ezekial Bahar at the University of Nebraska (Lincoln, NE)—appears promising (see figure). Bahar's theory, which in its current form is a single-scatterer theory, appears to have elements that give rise to enhanced backscatter.

The final set of experiments[4] was also performed at optical wavelengths. A spectacular set of observations, partly explained by classical electromagnetics, is shown. These experiments are germane to the atmospheric limitations on the propagation of high-intensity laser beams.



Bistatic scattering from a rough aluminum surface

Bahar's theory shows good correlation with the experiments performed by Mendez and O'Donnell. The surface is aluminum with RMS height fluctuations of 1.5 μm. It was illuminated with a 0.63-μm optical source at an incidence angle of 20 deg.

References

1. A. Ishimaru and Y. Kuga, "Attenuation constant of a coherent field in a dense distribution of particles," *Journal of the Optical Society of America*, Vol. 72, (1982), pp. 1317-1320.

2. Y. Kuga and A. Ishimaru, "Retroreflectance from a dense distribution of spherical particles," *Journal of the Optical Society of America-A*, Vol. 1, (1984), pp. 831-835.

3. E.R. Mendez and K.A. O'Donnell, "Observations of depolarization and backscattering enhancement in light scattering from Gaussian random surfaces," *Optics Communications*, Vol. 61, (1987), pp. 91-95.

4. R. Chang, et al., "Simulated Raman scattering, phase modulation and coherent antistokes Raman scattering from single micrometer-size liquid droplets,"

PROGRESS REPORT # 2

1. SFRC Number: N00014-87-K-0177

2. PERIOD COVERED: January 1, 1988 - June 30, 1988

3. TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

4. SPONSOR: Office of Naval Research

5. SCIENTIFIC PROGRAM OFFICER: Drs. R. J. Hansen and David Johnson

6. PRINCIPAL INVESTIGATOR: Ezekiel Bahar

7. NAME OF INSTITUTION: University of Nebraska-Lincoln

8. AUTHOR OF REPORT: Ezekiel Bahar

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD

See Attached List

10. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator
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Graduate Research Assistants

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9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(9.1a) Papers Presented at Technical Meetings

(i) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988. "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

(ii) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse, University, Syracuse, New York, June 6-11, 1988. "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."

(9.1b) Papers Accepted for Presentation at Technical Meetings

(i) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. "Scattering, Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(9.2) Papers Submitted to Journal Editors for Review

(i) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors.

(ii) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity" with M.A. Fitzwater, Journal of Wave-Material Interaction.

(iii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M.A. Fitzwater, Journal of Wave-Material Interaction.

(iv) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C.M. Herzinger and M.A. Fitzwater.

(9.3) Papers Accepted for Publication

(i) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M.A. Fitzwater, Journal of the Optical Society of America, A, in press.

(ii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, in press.

(iii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M.A. Fitzwater, Journal of Wave-Material Interaction, in press.

(9.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Comparison of Unified Full-Wave Solutions for Normal-Incidence Microwave Backscatter From Sea with Physical Optics and Hybrid Solutions," With D.E. Barrick and M.A. Fitzwater, International Journal of Remote Sensing, Vol. 9, No. 3, pp. 365-377, 1988.

Outline of Research Findings

During this reporting period (January 1, 1988-June 30, 1988), the Principal Investigator presented two papers (see (Item 9.1a)). He has been invited to present a paper at the International Working Group Meeting on "Wave Propagation in Random Media" (see Item (9.1b)). Four technical/scientific papers were submitted for publication (see Item (9.2)) and three papers were accepted for publication. One paper was published in the International Journal of Remote Sensing on the comparison of the unified full wave solution for microwave backscatter from sea with physical optics and hybrid solutions.

Rob Kubik (M.S. Graduate Student) represented the University of Nebraska research group at the Quarterly Program Review Meeting held on March 29, 1988 at the David Taylor Research Center (Carderock, Maryland). His oral progress report covered the following topics:

1. Scattering Cross Sections for Rough Sea with Swell.

2. Scattering Cross Sections for Rough Surfaces with Non-Gaussian height and slope probability density functions.

3. Synthetic Aperture Radar (SAR) cross sections for rough surfaces with non-Gaussian surface height spectral density (Fourier transform of surface height correlation) functions.

4. Full Wave solutions for surfaces exhibiting enhanced backscatter.

5. Multiple scattering contributions to rough surface scattering.

Since the presentation of the oral progress report at the Quarterly Program Review Meeting, several advances have been made related to the topics listed above.

1. A polarimetric study has been initiated on remote sensing of the presence of remotely generated swell in rough sea. For normal incidence the two-scale hybrid (perturbation-physical optics) model of the rough sea does not distinguish between the radar returns for waves that are linearly polarized parallel to or perpendicular to the direction of the remotely generated swell. The analysis based on the full wave approach indicates that there is a significant polarimetric difference in the radar return even for normal incidence. In order to determine the principal parameters of the swell (direction, dominant wavelength, mean square slopes and height), all the elements of the (4x4) Stokes matrix (including the radar cross sections) are examined in this study.

2. The unified full wave approach has been used to determine the radar like and cross polarized cross sections for rough surfaces with non-Gaussian height and slope statistics (which decorrelate at very large distances between two points on the rough surface). The most significant differences between these preliminary results and the earlier results (based on the two-scale model of rough sea) are associated with the cross polarized cross sections.

3. The modulation of the like and cross polarized SAR cross sections by the tilt of the large scale surface parallel to and perpendicular to the plane of incidence, has been computed using the unified full wave approach. Here too, the most significant differences between this work and earlier work, is associated with the cross polarized cross sections. Furthermore, the two-scale model is not valid near normal incidence since the physical optics results are insensitive to fluctuations in the local tilt angles.

4. The manuscript on the enhanced backscatter has been revised. The major revision involves the inclusion of an appendix in which the principal equations presented in earlier manuscripts have been summarized.

5. To facilitate the investigation on the effects of multiple scattering (which involves the evaluation of multiple dimensional integrals), one of our graduate research assistants will attend an NSF-sponsored workshop at the Super Computer Facility, Cornell University.

PROGRESS REPORT # 3

1. SFRC Number: N00014-87-K-0177

2. PERIOD COVERED: 1 July 1988 - 31 December 1988

3. TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

4. SPONSOR: Office of Naval Research

5. SCIENTIFIC PROGRAM OFFICER: Dr. David Johnson

6. PRINCIPAL INVESTIGATOR: Ezekiel Bahar

7. NAME OF INSTITUTION: University of Nebraska-Lincoln

8. AUTHOR OF REPORT: Ezekiel Bahar

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD

See Attached List

10. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator

Research Associate Dr. M. A. Fitzwater

Graduate Research Assistants

DATE SUBMITTED: 31 January, 1988

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska-Lincoln
Lincoln, NE 68588-0511

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(9.1a) Papers Presented at Technical Meetings

(i) 1988 International Geoscience and Remote Sensing Symposium, Edinburgh University, Edinburgh, United Kingdom, September 13-16, 1988. "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," (FRA-221).

(ii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Scattering Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(9.1b) Papers Accepted for Presentation at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989. "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater.

(ii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989. "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(iii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989. "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

(iv) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989. "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths.

(9.2) Interim Reports

(i) Synthetic Aperture Radar Images for Swell Using the Unified Full Wave Method, with R. D. Kubik.

(9.3) Papers Accepted for Publication

(i) "Bistatic Incoherent Scattering Cross Sections for Two-dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187, April, 1988.

(ii) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Ocean (in press).

(iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 6, 33-43, January, 1989.

(9.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Scattering Cross Sections for Two-dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 3, 199-218, July, 1988.

(ii) "Scattering and Depolarization by Two-dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Wave Propagation and Scattering in Varied Media, Vol. 927, 78-87, April 6-8, 1988.

(9.4) Papers Published in the Technical Literature and Submitted with This Report (continued)

(iii) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 5, 1873-1883, November, 1988.

(iv) "Bistatic Incoherent Scattering Cross Sections for Two-dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187, April, 1988.

Outline of Research Findings

During this reporting period (1 July 1988 - 31 December 1988), the Principal Investigator presented two (2) papers (see Item (9.1a)) at Scientific/ Technical Meetings and four (4) papers have been accepted for presentation in the next few months (see Item 9.1b). An interim report on synthetic aperture radar images has been submitted to the project monitor (see Item (9.2)). Three (3) papers were accepted for publication (see Item (9.3)) and four (4) papers were published (see Item (9.4)). Reprints of the published papers have been submitted with this report.

Rob Kubik (M.S. Graduate Student) represented the University of Nebraska Research Group at the Quarterly Program Review Meeting, held at Dynamics Technology, Inc., Torrance, California on August 30, 1988.

His oral progress report covered the following principal topics:

1. Detection and identification of swell in rough seas using the Mueller Matrix elements.
2. Like and cross polarized scattering cross sections for a set of random rough surfaces that are characterized by non-Gaussian height and slope statistics.
3. Multiple scattering by random rough surfaces.
4. Tile modulation ("in" and "perpendicular" to the plane of incidence) of the Synthetic Aperture Radar Cross Sections for rough seas.

In addition to the topics discussed at the oral presentation, advances have been made in several related areas.

1. The polarimetric scattering data for an anisotropic model of the rough sea (with swell) is currently being analyzed with the objective of determining which elements of the (4x4) Stokes matrix (which includes the like and cross polarized radar cross sections) can be used to reliably detect the presence of swell and to identify its principal parameters (direction, dominant

wavelength, area square slope and height).

2. The like and cross polarized radar cross sections for a family of rough surfaces with non-Gaussian height and slope statistics have been evaluated using the unified full wave approach. For these rough surfaces, decorrelation implies statistical independence. Consideration is being given to devise practical ways that can be used to determine the rough surface statistics using these numerical results based on the unified full wave approach.
3. In order to account for multiple scattering by rough sea surfaces, two different analytical approaches are currently under investigation. Only one dimensionally rough surfaces are being considered at this time for this phase of our work. In the first approach, we seek numerical solutions to the (full wave) generalized telegraphists' equations. The singular nature of these integro-differential equations is one of the most difficult aspects of this problem. The second approach involves the evaluation of third order iterative solutions to the telegraphists' equations. These solutions can be expressed as multidimensional integrals. Using stationary phase integration techniques to analytically evaluate these integrals (in the high frequency limit), it is shown that the third order iterative solutions correspond to incident waves that are specularly scattered twice by the rough surface. (The primary and single scatter solutions correspond to the first and second order iterative solutions of the generalized telegraphists' equations). However, when the high frequency stationary phase solutions are not valid, the principal problem with the second approach is the excessive time it takes to evaluate the multiple integrals even with super computers. The principal investigator will be awarded 95 hours of computational time on the NSF supported Super Computer Center at Cornell University beginning January 1, 1989. Progress in

this phase of our research will be significantly facilitated through the use of this Supercomputer Grant.

4. When the mean plane of the sea surface that is effectively illuminated by the Synthetic Aperture Radar (SAR), is tilted (with respect to a fixed plane of incidence) by the relatively large scale components of the rough sea surface, the like and cross polarized SAR backscatter cross sections are modulated. The analysis of these tilt modulations ("in" and "perpendicular" to the plane of incidence), provides significant insight into developing polarimetric techniques for the detection of sea swell and ship wakes (see Interim Report Item 9.2). During this reporting period progress has been made on the efficient evaluation of the like and cross polarized backscatter cross sections for rough surfaces with arbitrarily oriented mean planes. This is done by storing numerical data on four key elements of the Stokes' matrix. This work will facilitate the rapid evaluation of the scattering cross sections for several thousand pixels over a large segment of the sea surface.

5. The analytical and computational work on the horizontally and vertically polarized incoherent bistatic cross sections for one-dimensionally rough perfectly conducting surfaces is near completion. In this work, which is based on the unified full wave approach, the random rough surface is characterized by a four-dimensional Gaussian probability density function for the surface heights and slopes at two points on the surface. Thus all the correlations between the surface heights and slopes at two points on the rough surface are accounted for in the analysis. The corresponding physical optics and small perturbation solutions are also evaluated. When the rough surface slopes are assumed to be negligibly small (as in

the analysis of Rice (1951)), the full wave analysis reduces to the small perturbation results. However, when it is assumed (in the high frequency limit) that the major contributions to the scattered fields come from the neighborhoods of the stationary phase points on the rough surface, the full wave solutions are in agreement with the physical optics solution. There is good agreement in general between the full wave, small perturbation and physical optics solutions for scattering in the near specular direction, when the mean square slopes are very small compared to unity and the mean square heights are very small compared to the wavelengths of the electromagnetic excitations. For backscatter this is not the case.

In this work it is also shown that shadowing effects are very significant. Furthermore, it is shown that surfaces characterized by different spectral density functions, but with the same mean square slopes and correlation lengths, have significantly different bistatic cross sections.

6. The existing computer codes for the bistatic like and cross polarized scattering cross sections of two dimensionally rough surfaces have been revised such that the cross sections can be evaluated for any scatter direction (not just in the plane of incidence). The cross sections in the direction normal to the mean plane are multiple valued functions of the azimuth angle, however the total scattered power is single valued. Methods for presenting these new three dimensional data (in the half-space above the sea surface) are presently under study.
7. The computer codes for scattering by two dimensionally rough surfaces have also been updated to account for both (vertical and horizontal) linearly polarized excitations as well as (right and left) circularly

polarized excitations. Thus four linearly polarized cross sections σ^{VV}, σ^{HH}, σ^{HV}, σ^{VH} (V-vertical, H-horizontal) and four circular polarized cross sections σ^{RR}, σ^{LL}, σ^{LR}, σ^{RL} (R-right circular, L-left circular) can now be evaluated. These new results can be used to enhance our ability to interpret measured data.

Reference

Rice, S. O. (1951), Reflection of Electromagnetic Waves from Slightly Rough Surfaces, The Theory of Electromagnetic Waves, Interscience Publishers, Inc., New York, NY.

PROGRESS REPORT # 4

1. SFRC Number: N00014-87-K-0177

2. PERIOD COVERED: 1 January 1989 - 30 June 1989

3. TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

4. SPONSOR: Office of Naval Research

5. SCIENTIFIC PROGRAM OFFICER: Dr. David Johnson

6. PRINCIPAL INVESTIGATOR: Ezekiel Bahar

7. NAME OF INSTITUTION: University of Nebraska-Lincoln

8. AUTHOR OF REPORT: Ezekiel Bahar

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD

See Attached List

10. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator
Graduate Research Assistants

DATE SUBMITTED: 31 July 1989

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Department of Electrical Engineering
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LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTINT PERIOD, INCLUDING JOURNAL REFERENCES.

(9.1a) Papers Presented at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989, "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M.Fitzwater.

(ii) IEEE AP-S International Symposium and URSI Radio Science Meeting, June 26-30, 1989, San Jose, California, "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."

(iii) 1989 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 26-30, 1989, "Transmission Scattering and Depolarization Across Rough Surfaces -Full Wave Solutions," with Guorong Haung.

(9.1b) Papers Accepted for Presentation at Technical Meetings

(i) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(ii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

(iii) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."

(iv) National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, Massachusetts. Invited paper on Electromagnetic Scattering by Randomly Rough Boundaries.

(v) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989, "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(vi) U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, MD, August 3, 1989, Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach with S.M. Haugland and A.H. Carrieri.

(vii) International Union of Radio Science Commission F Symposium on Radio and Nonionized Media at La Londe-les-Maures, France, Sept. 11-15, 1989, "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes-Full Wave Approach," with R. Kubik.

(9.2) Papers Submitted to Journal Editors for Review

(i) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, in press.

(ii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS "89 Conference on Remote Sensing, Vancouver, Canada, in press.

(iii) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, in press.

(iv) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, in press.

(9.2) continued

(v) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited paper on Review of Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Directions in Electromagnetic Research, Boston, Massachusetts, in press.

(vi) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts.

(9.3) Papers Accepted for Publication

(i) "Non Specular Scattering by Irregular Layered Media," Proceedings of the 1988 Scientific Conference on Obscuration and Aerosol Research, in press.

(ii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS "89 Conference on Remote Sensing, July 10-14, 1989, Vancouver, Canada, in press.

(iii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, July 4-10, 1989, Vancouver, Canada, in press.

(iv) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 146-147, July, 1989.

(9.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M.A. Fitzwater, Journal of the Optical Society of America, A, Vol. 6, pp. 33-43, January, 1989.

(ii) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Oceans, Vol. 94, No. C2, pp. 2159-2169, February, 1989.

(9.5) M.S. Thesis Completed during this reporting period

(i) "Scattering Cross Section Modulation of a Synthetic Aperture Radar Resolution Cell with Application to SAR Imaging Unified Full Wave Approach," by Robert D. Kubik.

Outline of Research Findings

During the reporting period (1 January 1989 - 30 June 1989), the principal investigator presented three papers at Scientific/Technical meetings (see Item (9.1a) and seven papers have been accepted for presentation in the next few months (see Item (9.1b)). Six papers were submitted for publication (see Item (9.2)) and four papers were accepted for publication (see Item (9.3)). Two papers were published (see Item (9.4)). Reprints of these papers have been submitted with this report. The M.S. Thesis by R. Kubik, was accepted. (Item (9.4)).

Progress has been made in the following research areas during this reporting period. Details are given in preprints of research findings submitted to contract monitor--see Item (9.2).

1. Polarimetric detection and identification of sea swell at normal and oblique incidence.
2. Unified full wave solutions for the like- and cross polarized scattering cross sections of rough sea surfaces with non-Gaussian height and slope statistics. Special emphasis is given to identifying the most discriminating scattering characteristics of the surfaces with different height and slope probability density functions.
3. Multiple scattering by rough surfaces. For surfaces with large mean square slopes multiple scatter for near normal incidence could be significant if the surfaces are highly reflecting. Full wave solutions for the single and double scatter field have been computed using the NSF supported Super Computer facility at Cornell University.
4. Tilt modulations (in and perpendicular to the plane of incidence) of the Synthetic Aperture Radar Cross Sections for rough seas.

   In this work the unified full wave approach accounts for both the small and large scale spectral components of the rough sea. Thus the tilt

modulation for both the like- and cross-polarized cross sections are evaluated for all angles of incidence.

5. Development of efficient computer codes to obtain simulations of Synthetic Aperture Radar Polarimetric Images of sea surface. These programs reuse stored data related to four elements of the Mueller (Phase) matrix.

6. Evaluation of the bistatic cross sections for surfaces characterized by four dimensional Gaussian joint probability density functions. Thus the correlations between the surface heights and slopes at two points of the surface are fully accounted for in the analysis.

7. Computation and graphical representation of the like- and cross-polarized bistatic scattering cross sections of rough surfaces for arbitrary scatter angles in the entire half space above the sea surface (not just the plane of incidence).

PROGRESS REPORT #5

SFRC Number: N00014-87-K-0177

PERIOD COVERED: 1 June 1989 - 31 December 1989

TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

SPONSOR: Office of Naval Research

SCIENTIFIC PROGRAM OFFICER: Dr. David Johnson

PRINCIPAL INVESTIGATOR: Ezekiel Bahar

NAME OF INSTITUTION: University of Nebraska-Lincoln

AUTHOR OF REPORT: Ezekiel Bahar

LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP *DURING THIS REPORTING PERIOD*

See Attached List

). SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator
Graduate Research Assistants

AE SUBMITTED: 31 January 1990

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LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES.

(9.1a) Papers Presented at Technical Meetings

(i) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(ii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

(iii) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."

(iv) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Scattering Cross Sections and Backscatter Enhancement for two Dimensional Rough Surfaces with Different Correlation Lengths".

(v) National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, Massachusetts, Invited paper on Electromagnetic Scattering by Randomly Rough Boundaries.

(vi) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989, "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(vii) International Union of Radio Science Commission F Symposium on Radio and Non-ionized Media at La Londe-les-Maures, France, September 11-15, 1989, "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach", with R. Kubik.

(viii) Scientific Conference on Chemical Defense Research, U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, Maryland, November 14-17, 1989, Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach with S. M. Haugland and A. H. Carrieri.

(9.1b) Papers Accepted/Submitted for Presentation at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 3-5, 1990, Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solution, with G. Huang.

(ii) International Union of Radio Science (URSI, Commission F) Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, Hyannis, Massachusetts, May 16-18, 1990, "Remote Sensing of the Sea Surface Contaminated by Monomolecular Oil Slick: Full Wave Approach, with R. Kubik.

(iii) 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties, University of Maryland, College Park, Maryland, May 20-24, 1990, Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections: Full Wave Approach, with Y. F. Li.

(iv) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering From Rough Surfaces", with M. El-Shenawee.

(v) XXIIIrd General Assembly of the International Union of Radio Science, Prague, Czechoslovakia, August 28 - September 5, 1990, "Radiowave Propagation Over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters", Invited Paper.

(vi) International Union of Radio Science Symposium on Scattering From Random Media (Joint Session B/F), Prague, Czechoslovakia, August 28 - September 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces".

(9.2) Papers Submitted to Journal Editors for Review

(i) Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions, submitted for review.

(ii) Unified and Two Scale Full Wave Solutions to Interpret Apollo Lunar Surface Data with M. Haugland, submitted for review.

(iii) Tilt Modulation of Synthetic Aperture Radar Backscatter Cross Sections: Unified Full Wave Approach with R. Kubik, submitted for review.

(iv) Computer Simulation of Synthetic Aperture Polarimetric Images - Unified Full Wave Approach with R. Kubik, submitted for review.

(v) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions" with G. Huang, submitted for review.

(vi) "Scattering Cross Sections for Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach" with Y. F. Li, submitted for review.

(vii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach" with Y. F. Li, submitted for review.

(viii) "Statistics for Identifying Contaminated Rough Surfaces by Polarized IR Scattering: Full Wave Approach" with S. M. Haugland and A. H. Carrieri, submitted for review.

(ix) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, submitted for review.

(9.3) Papers Accepted for Publication

(i) "Physical Models of Nonspecular Scattering in Irregular Stratified Media", Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, Stockholm, Sweden, August 14-17, 1989, in press.

(ii) Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach, with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France, September 11-15, 1989, in press.

(iii) Electromagnetic Wave Scattering by Randomly Rough Boundaries, Invited paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research, Boston, Massachusetts, July 29, 1989, in press.

(9.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media", with M. A. Fitzwater, IEEE Transactions on Antennas and Propagation, Vol. AP-S 37, No. 12, pp. 1609-1616, December, 1989.

(ii) "Non Specular Scattering by Irregular Layered Media", Proceedings 1988 Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, CRDEC-SP , pp. 1-8, 1989.

(iii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach", with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-O, Vol. 3, pp. 1292-1295, July 10-14, 1989.

(iv) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach", with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-O, Vol. 3, pp. 1296-1299, July 4-10, 1989.

(v) Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths, Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 146-147, July, 1989.

(vi) Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces, Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 398-399, July, 1989.

(9.5) M.S. Thesis Completed During this Reporting Period

(i) "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution by Yan-Feng Li.

Outline of Research Findings

During the reporting period (1 July 1989 - 31 December 1989), the principal investigator presented eight papers at Scientific/Technical meetings (See Item (9.1a)) and six papers were accepted/submitted for presentation at Technical Symposia during the next few months (see Item (9.1b)). Nine manuscripts were submitted to Journal Editors for review (see Item (9.2)) and three papers were accepted for publication (see Item (9.3)). Six papers were published in journals/conference proceedings during this period (see Item (9.6)). Reprints of these papers have been submitted with this report. The M.S. Thesis, "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution", by Yan-Feng Li was accepted (see Item (9.5)). Copy of thesis is also enclosed.

Progress has been made in the following research areas during this reporting period. Technical details are provided in the preprints and reprints of research findings submitted to the contract monitor (see Item (9.2)).

1. Bistatic Scattering Cross Sections are evaluated for rough surfaces characterized by four dimensional Gaussian joint probability density functions for the rough surface slopes and heights. It is shown that if the surface slopes are assumed to be negligibly small and the Rayleigh parameter $\beta = 4k_0^2\langle h^2\rangle \ll 1$ (k_0 is the wave number and $\langle h^2\rangle$ is the mean square height) the full wave solutions reduce to the small

perturbation solution of Rice. However, if all the height and slope correlations are accounted for in the analysis, the full wave solution reduces to the physical optics solutions (see Item (9.2)(i)).

2. The unified full wave approach which accounts for specular point scatter as well as diffuse Bragg scatter in a self consistent manner is used to interpret Apollo Lunar Surface data. It correctly predicts the enhancement of the specularly reflected signal off the moon's surface as the angle of incidence increases (see Item (9.2)(ii)).

3. During this period, work has been completed on the computer simulation of Synthetic Aperture Polarimetric Images of the rough sea surfaces (see Items (9.2)(iii) and (iv)). This work was also presented at the Radio Science Commission F Symposium (see Item (9.1a)(vii)).

4. Analytical work on radiowave scattering and depolarization across rough surfaces has been completed. Work on the computer implementation of the work is currently in progress (see Item (9.2)(v)).

5. Work has been completed on the full wave solution for the scattering cross sections of rough surfaces with non-Gaussian statistics. Both real and synthetic aperture radars were considered. Methods were evaluated to distinguish between surfaces with different statistical characterizations (see Item (9.2)(vi) and (vii)).

6. Significant progress was made on the evaluation of the full wave single and multiple scatter field intensities from rough surfaces. The effects of varying the following parameters were investigated: angle of incidence, mean square slope, mean square height, correlation length and the complex permittivity of the scattering medium. It is shown that for near normal incidence, the multiple scatter contributions are significant for very rough (mean square slopes larger than unity) highly reflecting surfaces (see Item (9.2)(ix)).

PROGRESS REPORT # 6

1. SFRC Number: N00014-87-K-0177

2. PERIOD COVERED: 1 January 1990 - 30 June 1990

3. TITLE OF PROPOSAL: "Scattering and Depolarization by Rough Sea: Unified Full Wave Approach"

4. SPONSOR: Office of Naval Research

5. SCIENTIFIC PROGRAM OFFICER: Dr. David Johnson

6. PRINCIPAL INVESTIGATOR: Ezekiel Bahar

7. NAME OF INSTITUTION: University of Nebraska-Lincoln

8. AUTHOR OF REPORT: Ezekiel Bahar

9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD

See Attached List

10. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:

Professor Ezekiel Bahar - Principal Investigator
Graduate Research Assistants

DATE SUBMITTED: 15 July 1990

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9. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ONR SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(9.1a) Papers Presented at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, Jan. 3-5, 1990, Electromagnetic Scattering and Depolarization Across Rough Surfaces--Full Wave Solution with G. Huang.

(ii) First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos National Laboratory, Mar. 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(iii) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering from Rough Surfaces with M. El-Shenawee.

(iv) International Union of Radio Science (URSI), Commission F) Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, Hyannis, MA, May 16-18, 1990, "Remote Sensing of the Sea Surface Cotnaminated by Monomolecular Oil Slick: Full Wave Approach," with R. Kubik.

(v) 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties, University of Maryland, College Park, MD, May 20-24, 1990, "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections: Full Wave Approach, with Y. F. Li.

(vi) 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 25-28, 1990, "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with Mark Haugland.

(9.1b) Papers Accepted for Presentation at Technical Meetings

(i) XXIIrd General Assembly of the International Union of Radio Science, Prague, Czechoslovakia, Aug. 28 - Sep. 5, 1990, "Radiowave Propagation Over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters," Invited Paper.

(ii) International Union of Radio Science Symposium on Scattering from Random Media (Joint Session B/F), Prague, Czechoslovakia, Aug. 28 - Sep. 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces."

(iii) Advisory Group for Aerospace Research and Development Fall 1990, Electromagnetic Wave Propagation Panel Symposium on Use or Reduction of Propagation and Noise Effects in Distributed Military Systems, Rethymno, Crete, Greece, Oct. 15-19, 1990, "Utilization or Reduction of the Effects of Sea Clutter for Real and Synthetic Aperture Polarimetric Radars."

(iv) The Fourth Biennial IEEE Conference on Electromagnetic Field Computation, Toronto, Canada, Oct. 22-24, 1990, "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee.

(v) 1990 U.S. Army Chemical Research Development and Engineering Center Scientific Conference on Chemical Defense Research, Aberdeen, MD, Nov. 13-16, 1990, "Computation of Mueller Matrix Elements for Irregular Stratified Media - Full Wave Approach," with Mark Haugland.

(9.2) Papers Submitted to Journal Editors for Review

(i) "Acoustic Scattering by Two-Dimensionally Rough Interfaces Between Dissipative Acoustic Media - Full Wave, Physical Acoustics and Perturbation Solutions," submitted for review.

(ii) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions," submitted for review. Revised.

(iii) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li, submitted for review.

(9.3) Papers Accepted for Publication

(i) "Full Wave Solutions for the Scattering of Acoustic Waves Excited by Arbitrary Source Distributions in Irregular Layered Media," Wave Motion, in press.

(ii) "Full Wave Multiple Scattering From Rough Surfaces," with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

(9.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Scattering of Acoustic Waves in Irregular Layered Media - Full Wave Solutions," Wave Motion, Vol. 12, pp. 53-65, Jan. 1990.

(ii) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, Stockholm, Sweden, pp. 503-505, Aug. 14-17, 1989.

(iii) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France, pp. 7.1.1 - 7.1.4. Sep. 11-15, 1989.

(iv) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research, Boston, MA, pp. 311-314, July 29, 1989.

(v) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

(vi) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li, Proceedings of the International Geoscience and Remote Sensing Symposium, Vol. II, p. 1401-1403, May, 1990.

(9.5) M.S. Thesis Completed During This Reporting Period

(i) "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces, Full Wave Approach," by Guorong Huang.

Outline of Research Findings

During the reporting period (1 January 1990 - 30 June 1990), the principal investigator presented six (6) papers at Scientific/Technical Meetings (see Item #(9.1a)) and five (5) papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item #(9.1b)). Three (3) papers were submitted to Journal Editors for Review (see Item #(9.2)) and two (2) were accepted for publication (see Item #(9.3)). Six (6) papers were published in journals and conference proceedings (see Item #(9.4)) and reprints of these papers have been submitted with this report. The M.S. Thesis of Guorong Huang was accepted (see Item #(9.5), (copy of the thesis is also enclosed).

Progress has been made in the following research areas during the reporting period - 1 January 1990 - 30 June 1990. Technical details are provided in the preprints and reprints of the research findings and the M.S. Thesis submitted to the Contract Monitor (see Items #(9.3) and (9.4)).

1. Bistatic Scattering Cross Sections for Slightly Rough Surfaces

It is shown that the fields scattered by slightly rough surfaces cannot be characterized solely on the basis of the mean square heights and the mean square slopes of the surfaces. When the small heights (compared to wavelength) and small slopes are bounded, the full solutions are in agreement with Rice's first order small perturbation solutions. However, if the heights and slopes are characterized by an unbounded joint (four dimensional) Gaussian probability density function, specular point scattering dominates the solution except for near grazing angles of incidence and scatter where the full wave solutions are shown to vanish. Thus in this case the full wave solutions are in agreement with Beckmann's results except near grazing angles and/or when the impact of the self-shadow function becomes important. It is also shown how Rice's first

order, small perturbation solution can be related to the full wave single scatter solution through a phase modification and a coordinate transformation (see Item #(9.2),(ii)).

2. Analytical and Computational Work on Radiowave Scattering and Depolarization Across Rough Interfaces Between Two Media

This work has just been completed. For surfaces with large mean square slopes and small correlation lengths, the transmitted fields exhibit a very strong non-specular component that is physically analogous to the enhanced backscattered intensity observed from very rough surfaces #((9.1a),(i)). This work has also been presented as an M.S. Thesis by Guorong Huang in May 1990 #((9.5),(i)).

3. Evaluation of the Singly and Multiply Scattered Field Intensities

This work has been extended to two dimensionally rough surfaces with very large slopes. The computational work is being carried out at the University of Cornell Super Computer Facility sponsored by the National Science Foundation #((9.1a),(iii)). In order to cut down on computer time, some of the integrals (over the spatial and wavenumber variables) will also be evaluated analytically. Since the stationary phase points come in pairs about turning points of the surface (where the curvature vanishes), special procedures must be followed to evaluate the stationary phase integrals.

4. Radar Cross Sections of the Sea Surface Coated by Oil Slicks

The results of these investigations have been presented at the URSI Commission F Meeting (see Item #(9.1a),(iv)). This work can be applied to the development of techniques to remotely sense both naturally occurring slicks as well as accidental (or deliberate) occurrences of oil spills.

5. Statistical Characterization of Random Rough Surfaces

It is shown that the predications based on the tilt modulation of the back-scattered radar cross sections can be used to determine the statistical characterization of random rough surfaces. This work was presented at the IGARSS Meeting

#((9.1a),(v)) and published in the conference proceedings #((9.2),(iii)).

6. Rough Surface Scattering Cross Sections for Ultra-Wideband Radars

The paper presented at the Los Alamos Symposium on Ultra Wideband Radar #(9.1a),(ii) is based on the fact that the full wave approach can be applied to composite surfaces without resorting to an artificial decomposition of the surface into surfaces with small and large roughness scales compared to the electromagnetic wavelength.

9. REFERENCES

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1. Bahar, E., Depolarization of electromagnetic waves excited by distributions of electric and magnetic sources in inhomogeneous multilayered structures of arbitrarily varying thickness--Generalized field transforms, J. Math. Phys., 14(11), 1502-1509, 1973a.

2. Bahar, E., Depolarization of electromagnetic waves excited by distributions of electric and magnetic sources in inhomogeneous multilayered structures of arbitrarily varying thickness--Full wave solutions, J. Math. Phys., 14(11), 1510-1515, 1973b.

3. Bahar, E., Depolarization in nonuniform multilayered structures--Full wave solutions, J. Math. Phys., 15(2), 202-208, 1974.

4. Bahar, E., and M. A. Fitzwater, Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment, J. Opt. Soc. Am A, 6, 33-43, 1989.

5. Bahar, E., and M. A. Fitzwater, Co-polarized and Cross-polarized Incoherent Specific Intensities for Waves at Oblique Incidence Upon Layers of Finitely Conducting Particles of Irregular Shape, J. Opt. Soc. Am A, 4, 41-56, 1987.

6. Beckmann, P., and A. Spizzichino, The Scattering of Electromagnetic Waves from Rough Surfaces, Macmillan, New York, 1963.

7. Brown, G. S., Backscattering from a Gaussian-distributed perfectly conducting rough surface, IEEE Trans. Antennas Propag., AP-25(3), 472-482,

8. Rice, S. O., Reflection of electromagnetic waves from a slightly rough surface, Commun. Pure Appl. Math., 4, 351-378, 1951.

9. Valenzuela, G. R., Scattering of electromagnetic waves from a tilted slightly rough surface, Radio Sci., 3(11), 1051-1066, 1968.

10. Wright, J. W., A new model for sea clutter, IEEE Trans. Antennas Propag., AP-16(2), 217-223, 1968.

11. Zebkar, H. A., J. J. vanZyl, L. Horikane and F. Burnette, Calibrated imaging radar polarimetry: Technique examples and applications, Proceedings of the URSI Commission F Meeting, University of Maryland, College Park, Maryland, p. 100, May 1985.

10. ILLUSTRATIONS

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Figure (10.1) Principal properties of the Full Wave Approach.

Figure (10.2) Computed simulation of SAR image $\langle\sigma^{VV}\rangle$ for sea surface with swell.

Figure (10.3) Computed simulation of SAR image $\langle\sigma^{HH}\rangle$ for sea surface with swell.

Figure (10.4) Computed simulation of SAR image $\langle\sigma^{VH}\rangle = \langle\sigma^{HV}\rangle$ for sea surface with swell.

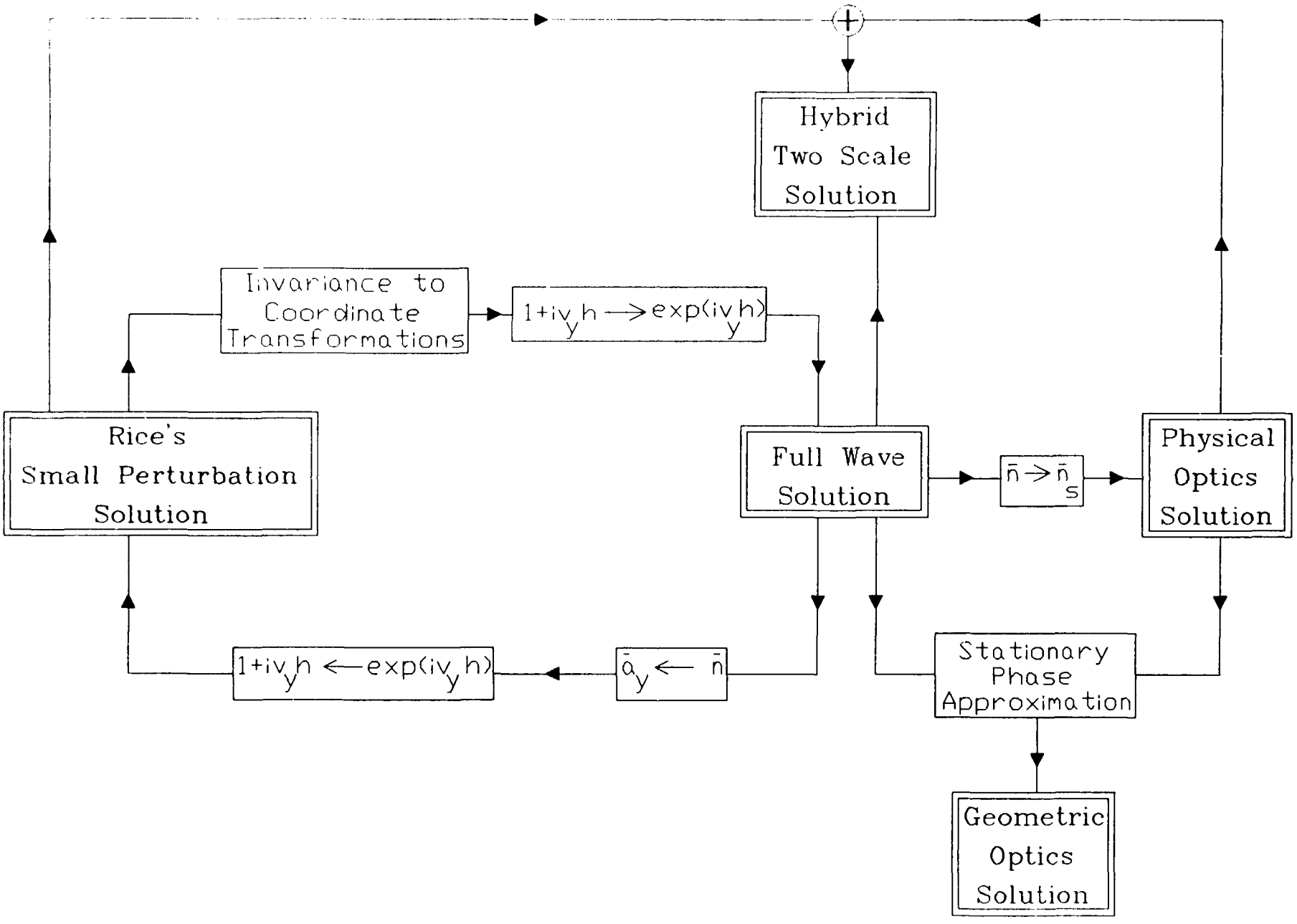

Fig. (10.1) Principal Properties of the Full Wave Approach.

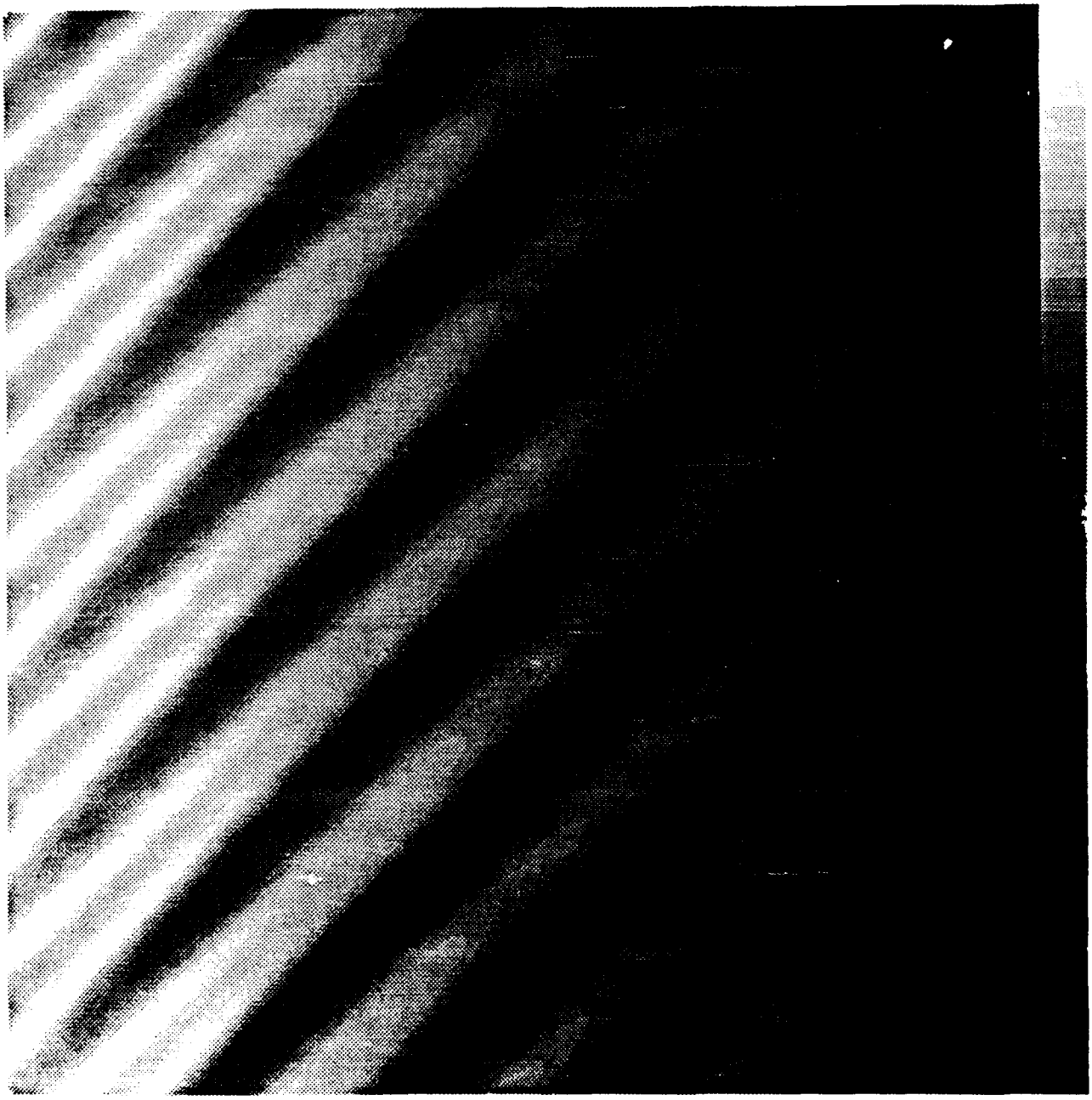

Fig. (10.2) Computer Simulation of SAR Image $\langle \sigma^{VV} \rangle$ for Sea Surface with Swell.

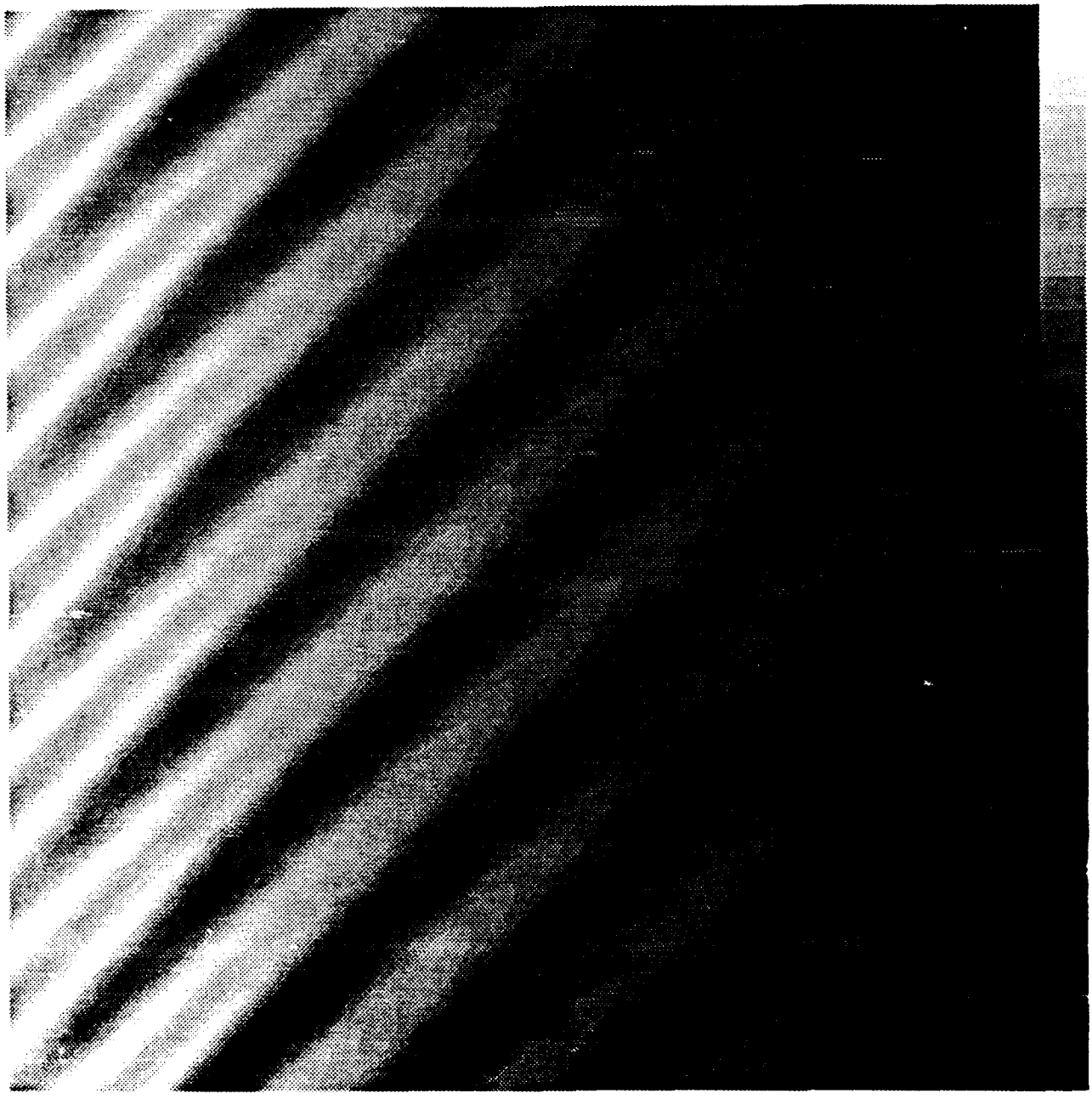

Fig. (10.3) Computer Simulation of SAR Image $\langle \sigma^{HH} \rangle$ for Sea Surface with Swell.

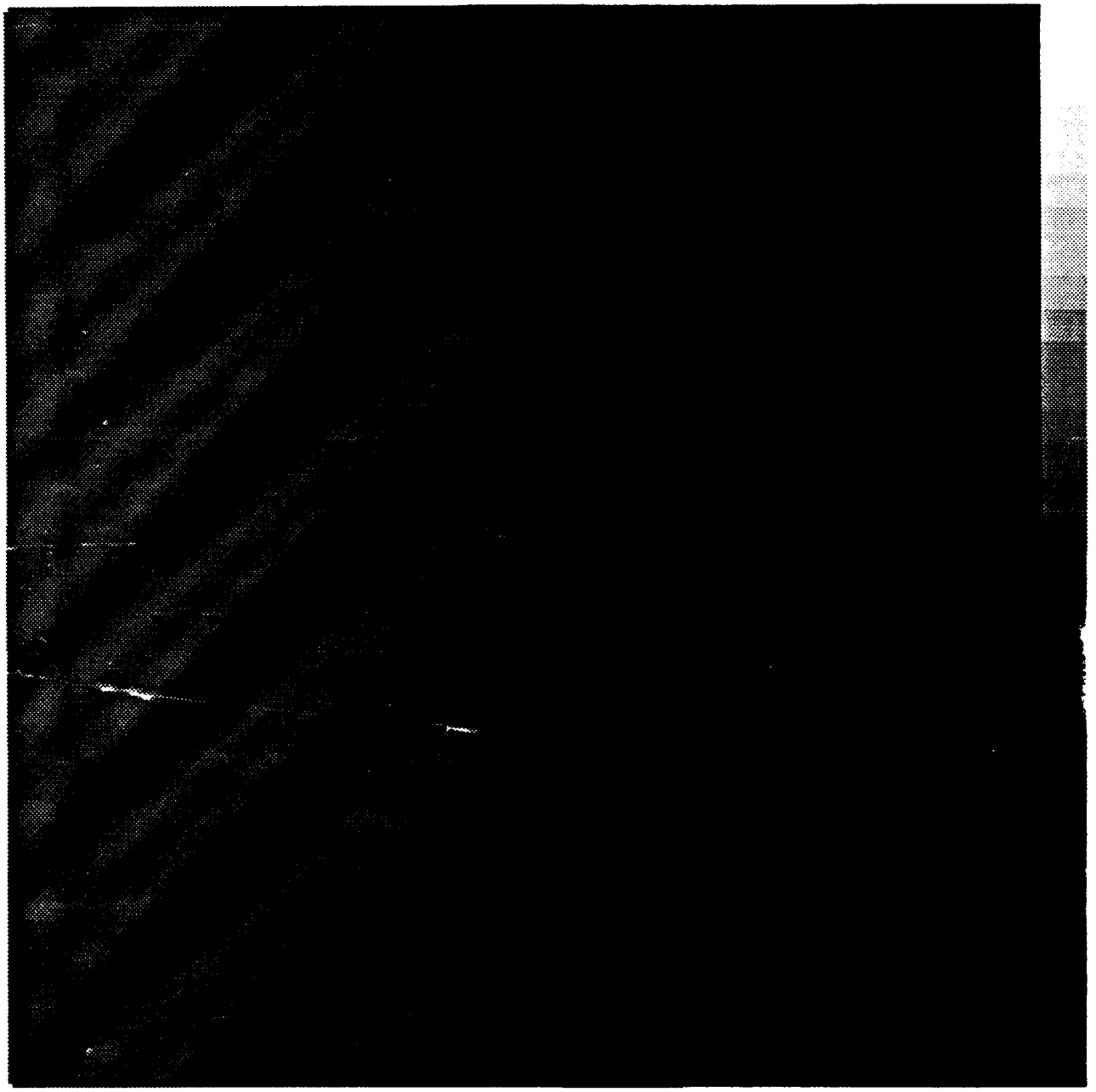

Fig. (10.4) Computer Simulation of SAR Image $\langle\sigma^{VH}\rangle$ = $\langle\sigma^{HV}\rangle$ for Sea Surface with Swell.